Modeling Spectra and Lightcurves from Supernovae

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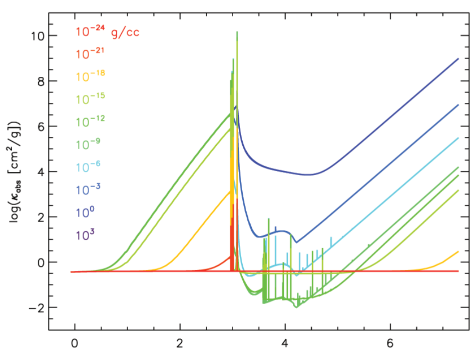
Massive stars at the end of their lives release huge amounts of energy in supernova explosions that can be detected across cosmological distances. Even if prior observations exist, such distances make supernova progenitors difficult to identify. New real-time surveys, like the Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), may detect supernovae (SNe) at very early times, giving us a rare view of these short-lived stars immediately after core collapse.

When the radiation-dominated shock wave from a core collapse approaches the stellar surface, the optical depth of the plasma ahead of the shock decreases until the radiation can escape in a burst. Gaining energy from the shock's kinetic energy via Compton scattering, this burst can be observable as an ultraviolet (UV) or X-ray flash, lasting for seconds to hours. If a dense stellar wind is present, shock breakout (SBO) can occur at the edge of the wind. Occurring days or weeks before the optical light from radioactive decay peaks, shock-breakout radiation can be used to determine the radius of the progenitor star or its recent mass loss history. This early detection of supernovae (SNe) allows spectra and luminosity observations to be made during the rising phase of the light curve as well as the decline.

Shock breakout was predicted nearly 40 years ago [1,2], but has only recently been observed as an early peak in the UV light curve [3,4], as infrared (IR) echoes in the Cassiopeia A SNe remnant [5], and directly as an X-ray burst in GRB 060218/SN2006aj [6] and XRO 080109/SN2008D [7]. Simulations can help match our theoretical understanding of core-collapse SNe and SBO to these observations. Analyses of these observations (for example, [4, 7-9]) have considered various progenitor stars and stellar environments, considering whether SBO occurs near the stellar surface or in a wind or shell. In all of these environments, SBO is treated as a single wavelength-independent event for which a single radius, temperature, and time scale can be observed or calculated. This assumes a gray opacity, which comparisons to monochromatic opacities can show to be invalid (see Fig. 1). We have developed a new code, Spectrum, to calculate spectra and lightcurves with monochromatic opacities and allow us to study SBO as a wavelength-dependent phenomenon. We describe the codes used for the SNe simulations presented here, the Spectrum code, and some preliminary results from this pipeline.

Fig. 1. Hydrogen opacity at 0.5 eV for a range of densities.



The results presented here are from a 1D simulation of a 23-solar-mass progenitor [10] that was evolved with the TYCHO stellar evolution code as a binary star. The H envelope is lost at the base of the red giant branch and the star evolves as a Wolf-Rayet star, ending as a 6.4-solar-mass star that explodes as a Type Ib SNe. A 1D code simulates core-collapse and the launch of the shock wave, and the central neutron star is replaced with a hard reflective boundary and a gravitational potential. After nuclear burning is finished, the output is mapped into RAGE (Radiation Adaptive Grid Eulerian), a multidimensional, multispecies Eulerian adaptive mesh refinement (AMR) radiation hydrodynamcs code [11]. RAGE uses a cell AMR scheme, allowing adjacent cell sizes to vary by no more than one level. We use two-temperature physics in which matter and radiation are coupled but can be at different temperatures. Each of up to 30 species is evolved with its own continuity equation.

Spectrum is a post-process code that takes density, temperature, velocity, and material mass fraction profiles as input and creates spectra for a wide wavelength range [12]. It uses monochromatic opacities from the LANL OPLIB database [13], which contains single-element opacities for local thermodynamic equilibrium (LTE) conditions. These opacities were accessed through the TOPS code for temperature and density pairs for 14,900 energies. Spectrum maps 1D data onto a 2D grid with a

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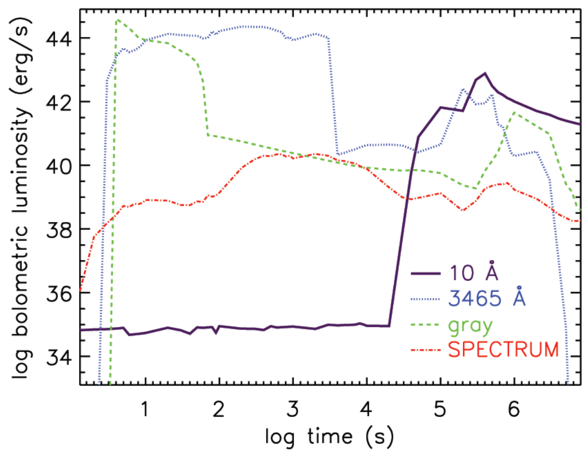

Fig. 2. Bolometric lightcurves using a blackbody approximation at a tau=1 radius calculated with monochromatic opacities at two wavelengths and a gray helium opacity, and the bolometric lightcurve from Spectrum.

specified number of zones in angle, uniformly spaced in cosine. Each of these fluid elements is assumed to be in LTE with its surroundings and to emit as a blackbody. This blackbody luminosity for each wavelength is attenuated along a line of sight through the material between that fluid element and the observer by integrating over the absorption opacity. These luminosity calculations also include the effects of Doppler shifting, time dilation, and limb darkening. Lightcurves are created by integrating over each spectra over a given wavelength band.

A variant of Spectrum continues to be developed to analyze dumps from the Advanced Simulation and Computing program (ASC) RAGE and Cassio codes that are simulating experiments on the National Ignition Facility, the Omega laser, and the Z-machine at SNL. This Spectrum code variant is able to calculated the exact diagnostics in these experiments, allowing a more direct comparison between simulation and experiment and allowing LANL scientists to do more rigorous verification and validation within its experimental program.

The radius (and time) at which shock breakout occurs is dependent on the opacity of the outer layers of the star and any surrounding wind or ejecta. Monochromatic opacities can vary by many orders of magnitude with wavelength, so a single radius and temperature cannot accurately describe this phenomenon. To study this phenomenon we used Spectrum to calculate the tau=1 surface (where the material becomes optically thick) using monochromatic opacities for a range of wavelengths, as well as a gray helium opacity. Using the Stefan-Boltzmann law, we calculated a bolometric luminosity using the radius and temperature at this surface for several wavelengths and the gray case, and compared these to the bolometric luminosity from the full Spectrum calculation (see Fig. 2). The single temperature and radius blackbody approximation overestimates the total luminosity, since no attenuation is present, and does not match the rise time or rate observed for a monochromatic

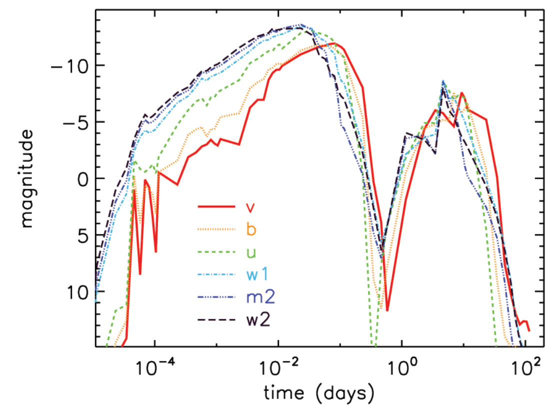

Fig. 3. Lightcurves for Swift UV/ Optical bands created with Spectrum.

calculation. Creating lightcurves for multiple wavelength bands using Spectrum shows how the observed peak luminosities, rise time, and duration changes with wavelength (see Fig. 3). A future paper will describe SBO in more detail for single and binary core-collapse SNe progenitors and explore the implications of the wavelength dependence of SBO for comparing simulations to observations.

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